Cost Savings from Applying Physics-of-Failure Analysis during System Development

To

National Defense Industrial Association

5th Annual

Systems Engineering Conference

Tampa, FL

22-24 October 2002

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US Army Materiel Systems Analysis Activity

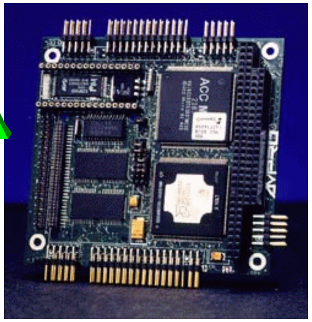
Outline

- Physics-of-Failure Overview
- Electronics applications
- Mechanical applications
- Physics-of-Failure approach to prognostics
- Summary

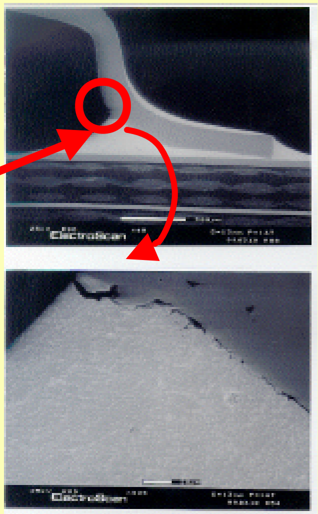
Physics of Failure

Stress (e.g., vibration) is propagated from system level to failure site

- Science-based approach to reliability
  - -Model the root causes of failure (e.g., fatigue, fracture, corrosion & wear)
- Failure models & CAD tools developed
  - - By industry/academia/government
  - - To address specific materials, sites, & architectures



Root-cause failure is cracking of solder joint



Benefits

- Design-in reliability
- Eliminate failures prior to test
- Better chance of passing test
- Increased fielded reliability
- Improved prognostics
- Decreased O&S costs

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Teradyne
Textron Systems
Thompson Computer Elect.
Triquint
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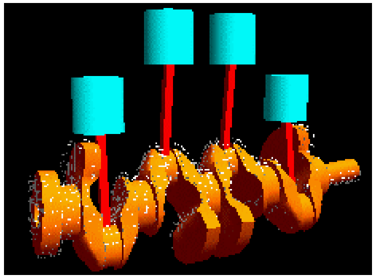
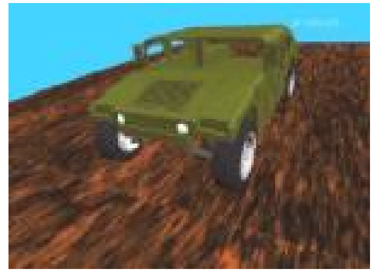
U.K. DERA
U.K. Ministry of Defence
U.S. Air Force WPAFB
U.S. Army AMSAA
U.S. Naval Surface Warfare
Visteon Automotive Controls

Partnership of Gov't, Industry, & Academia

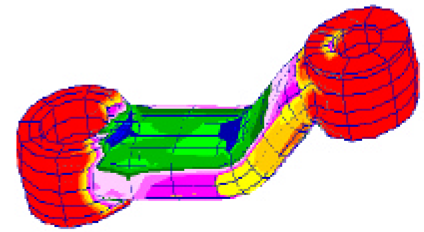
Physics of Failure Software Tools



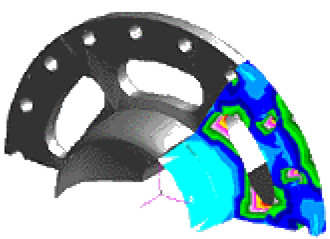
Solid Modeling Tools



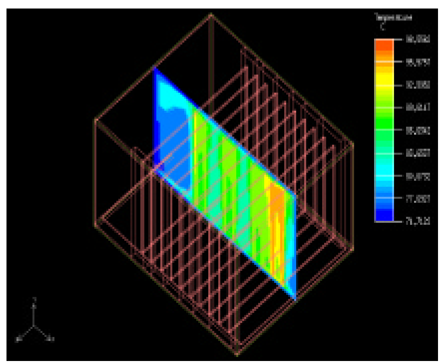
Dynamic Simulation Tools



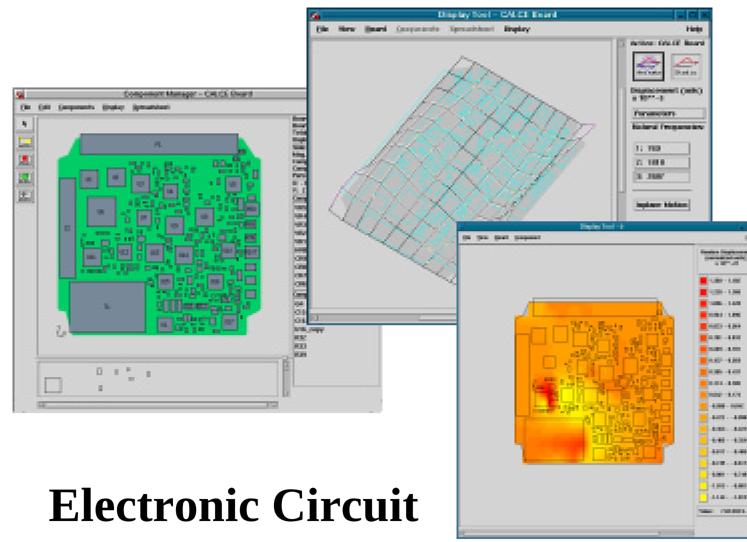
Finite Element Modeling Tools



Fatigue Analysis Tools



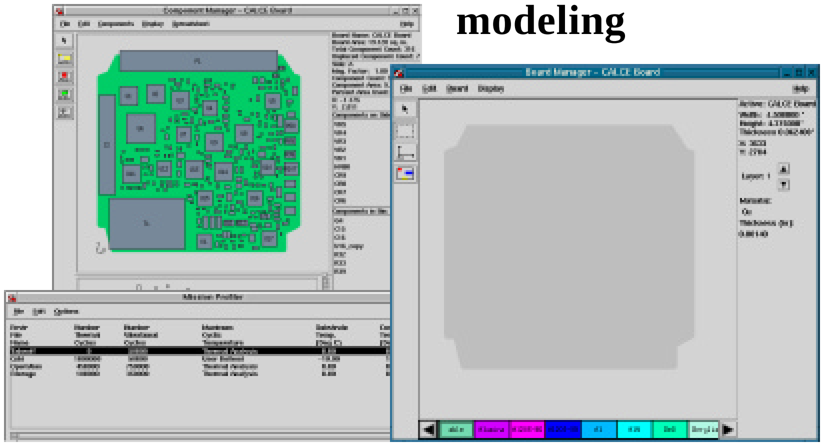
Thermal Fluid Analysis Tools



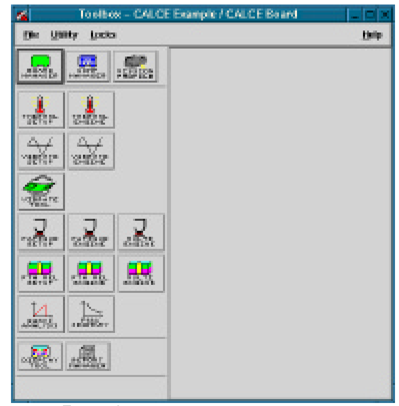
Electronic Circuit Card and IC Toolkits

UMD CalcePWA Software Tool

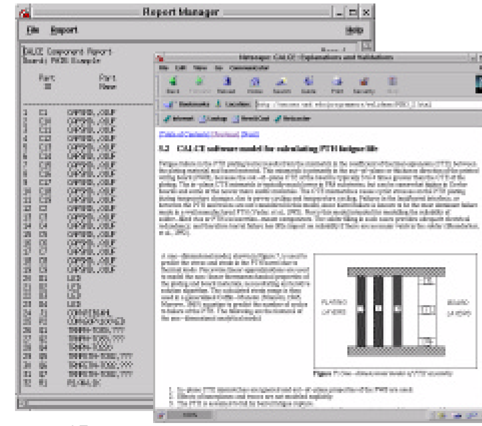
Architecture & environment modeling



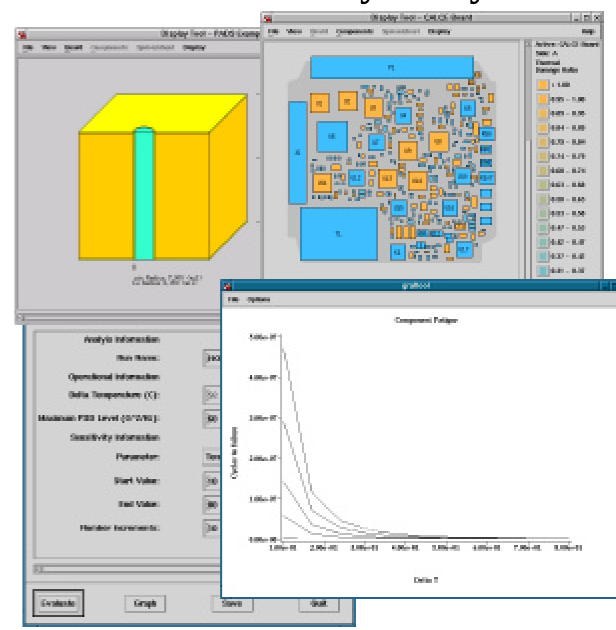
Toolbox



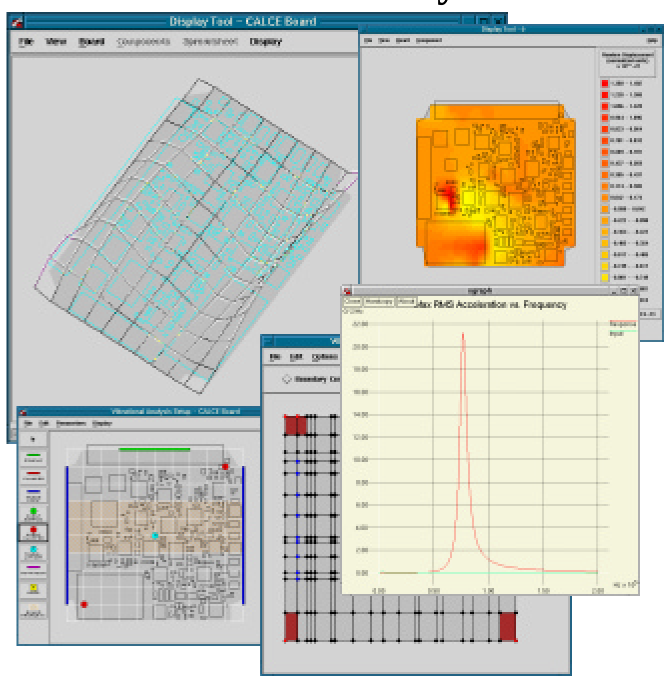
Reports and documentation



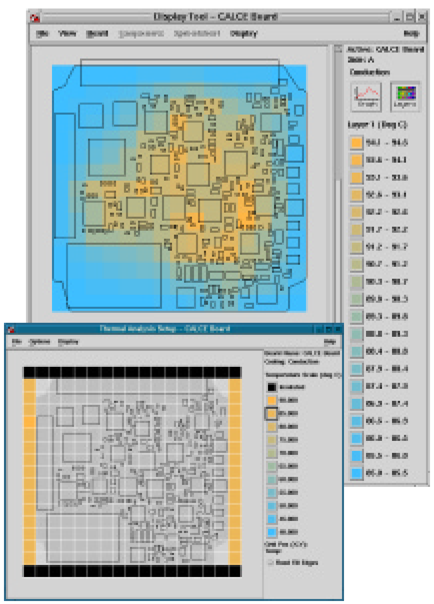
Failure assessment & sensitivity analysis



Vibration analysis



Thermal analysis

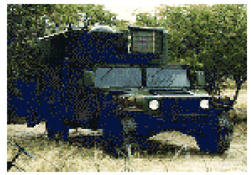


Electronics Physics of Failure Success Stories

Radar Ground Station

$1.2M Saved

- Analysis showed commercial circuit card OK
- AMSAA funded



Tracked Vehicle

Increased Reliability

- Identified potential thermal & vibration problems
- PM funded

Tri-Service Radio

$27M Cost Avoidance

- Identified weak link in design & verified
- ManTech funded

Air & Ground System Electronics

Design Changes Recommended

- Circuit card & box-level analyses
- Potential technology expansion
- PM funded

Army Helicopter

$50M Savings

- Air Force analysis showed commercial ICs OK
- AF ManTech funded

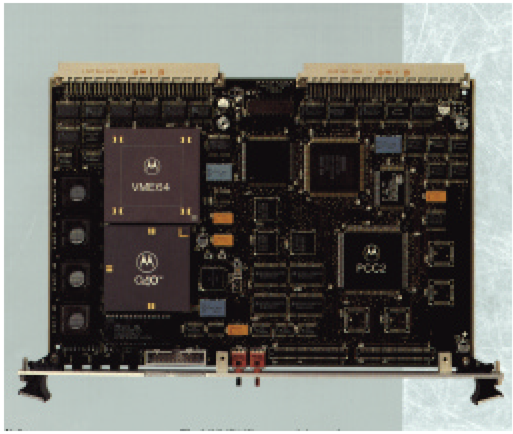
Missile System

- PoF analysis on Plastic Ball Grid Array
- PM funded

Evaluate New Technology

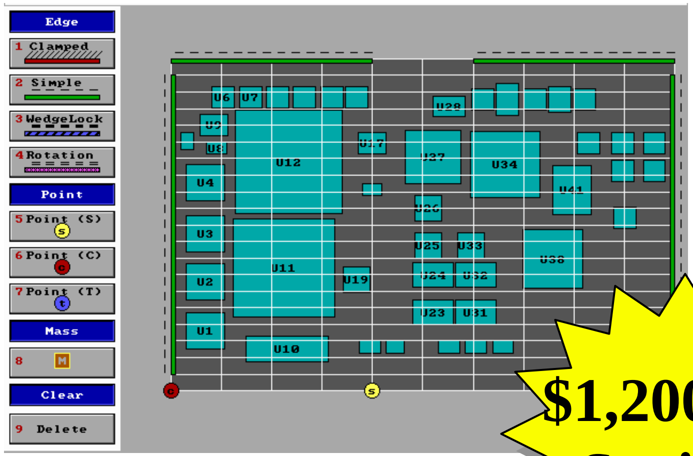
Ground Station Physics of Failure Analysis

Objective: **Determine whether Commercial Processor circuit card could be used instead of Ruggedized circuit card in the Ground Station**



Electronics Ground Station

Approach: **Performed vibrational, thermal and solder-joint fatigue analyses using CalcePWA software**



Vibration Setup

$1,200,000 Savings

Results: **Commercial circuit card Fatigue Life 11 Years versus 23 Years for Ruggedized, which was acceptable (Cost Savings - $12,000/Card)**

Tri-Service Radio Physics of Failure Analysis

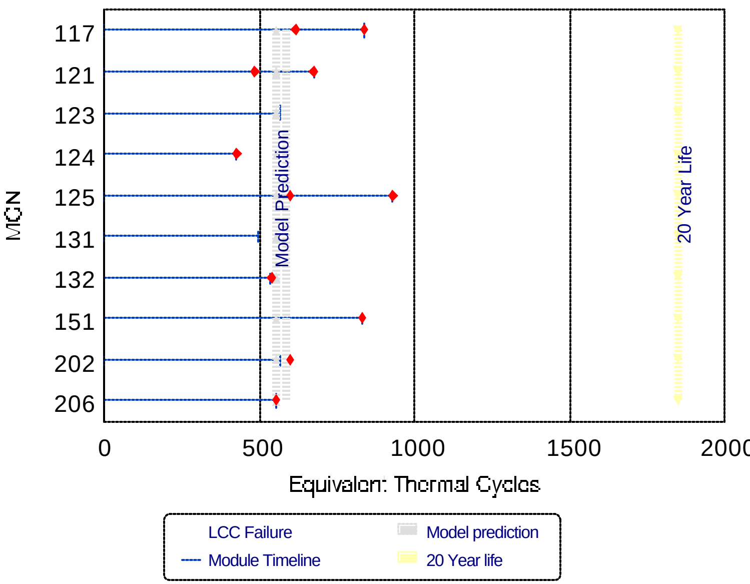
Objectives:

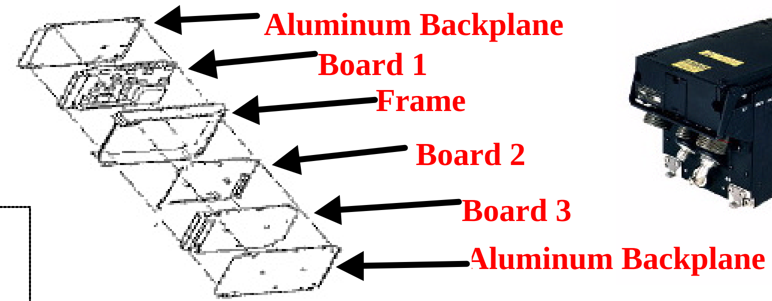
- Validate CalcePWA software through accelerated life testing
- Assess reliability of the module in a military environment
- Improve reliability of the module

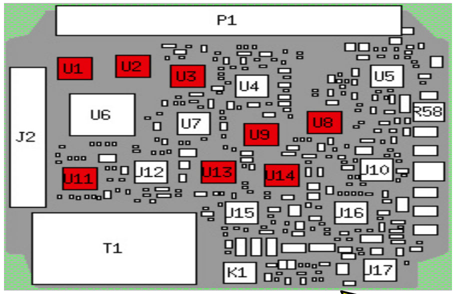
Analysis Results:

- 20 pin Leadless Chip Carrier was weak in design
- Estimated time-to-failure during accelerated life test cycle
- Estimated life under operating conditions - 6.5 years

Testing Results:







Developed Logistics Case Study

- 5,000 units fielded - 20 years field life

Operating & Support Cost Avoidance

$27,000,000

Failures occurred as predicted

Helicopter & Aircraft Physics of Failure Analysis

- **U.S. Air Force Project**
- **Aircraft and helicopter had common circuit cards**
- **CalcePWA software used to determine if commercial Integrated Circuits could be used**
- **Analysis show commercial Integrated Circuits could be used without degrading reliability**

Helicopter (Similar Savings for Aircraft)

- **Savings: Circuit Card #1: $18,501/card**
  Circuit Card #2: $20,228/card
- **For a buy of 1292, total savings = $50M**
- **Also a <u>15%</u> weight reduction per card**

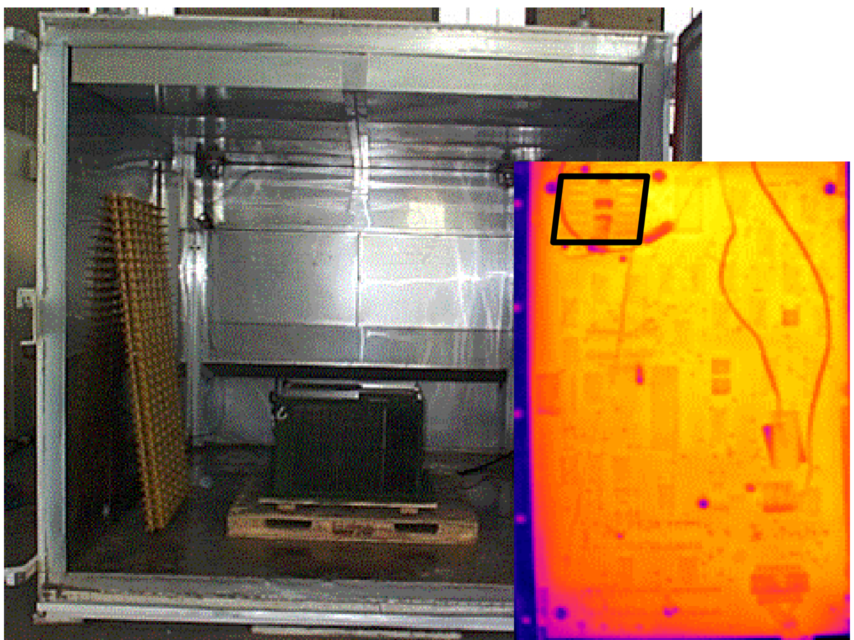
$50,000,000 Savings

Substantial savings for acquisition only.….would be greater if Operating and Support Costs were included

Recent Electronics PoF Analyses

Heater/Air Conditioner Unit

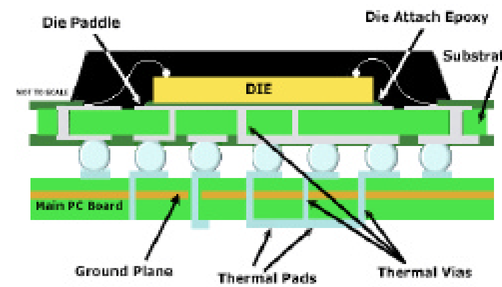
- PoF analysis on 2 circuit cards
- Thermal testing (initiated by AMSAA) on the unit
- Potential thermal problems & fixes identified
- Potential analysis for the unit



IR Image of CCA

Missile

- PoF Analysis on new packages (Ball & Column Grid Array)
- Analysis and accelerated life testing suggested that packages could be used for the missile



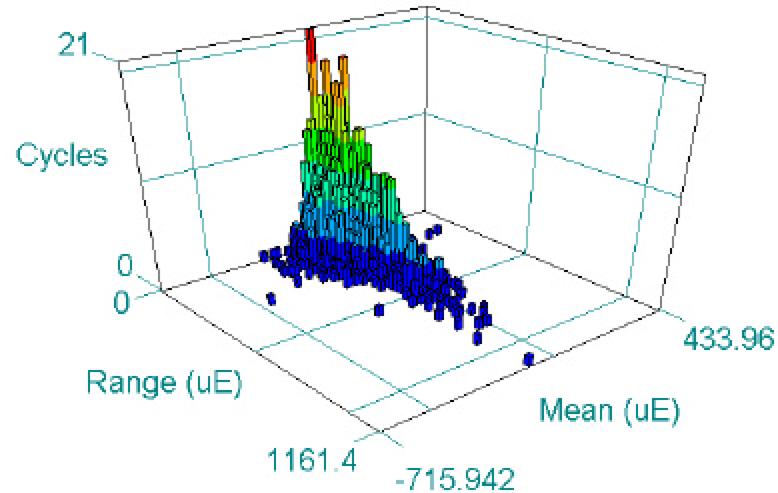
Accelerated Testing Results

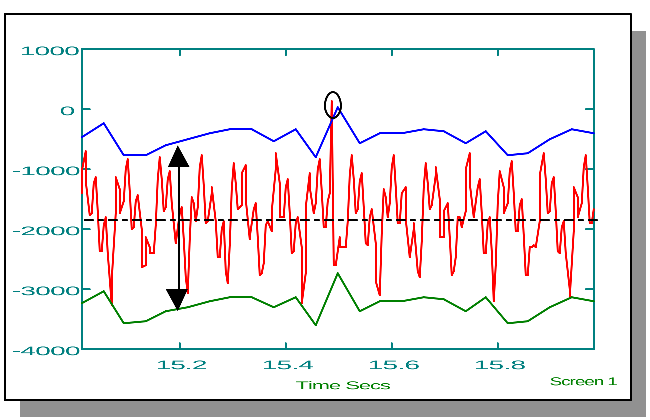
	Package 1 Median Time to Failure (cycles)	Package 2 Time to 1st Failure (cycles)
PoF Estimate	~2000-7000	~2500-3500
Actual	5389	6239 *(Better than Anticipated)*

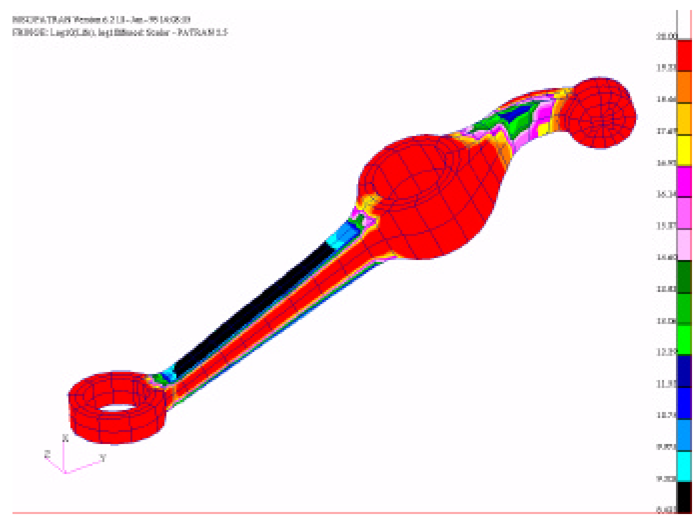
Mechanical Structures - Fatigue Analysis Software

Examples: nCode, LMS, University of Iowa DRAW

- Edits & characterizes strain time histories
- Rainflow counting & mean stress correction of strain cycles
- Estimates plastic strain based on elastic stress or strain calculations
- Calculates fatigue life based on measured (strain gauge) or FEA strain time histories



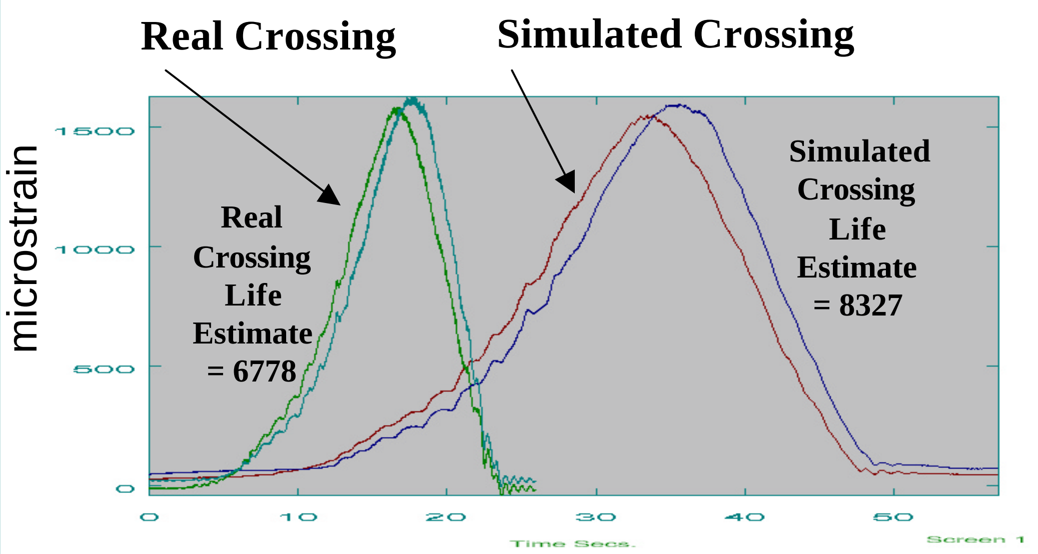




Fatigue Applied to Bridge Durability

- **Army Bridge**
  - User's 20-year durability requirement = 46,466 crossings
  - Test Requirement ˜ 3.8 x 46,466
  - Testing to requirement is unaffordable

Vehicle Crossings



PoF fatigue analysis tools used to:

- **Calculate fatigue life based on measured data inputs**
- **Compare fatigue equivalence (i.e. not stress level equivalence) for simulated vs actual crossing**

PoF Analysis Conclusion:

Increase Simulation load by 4% to achieve fatigue damage parity

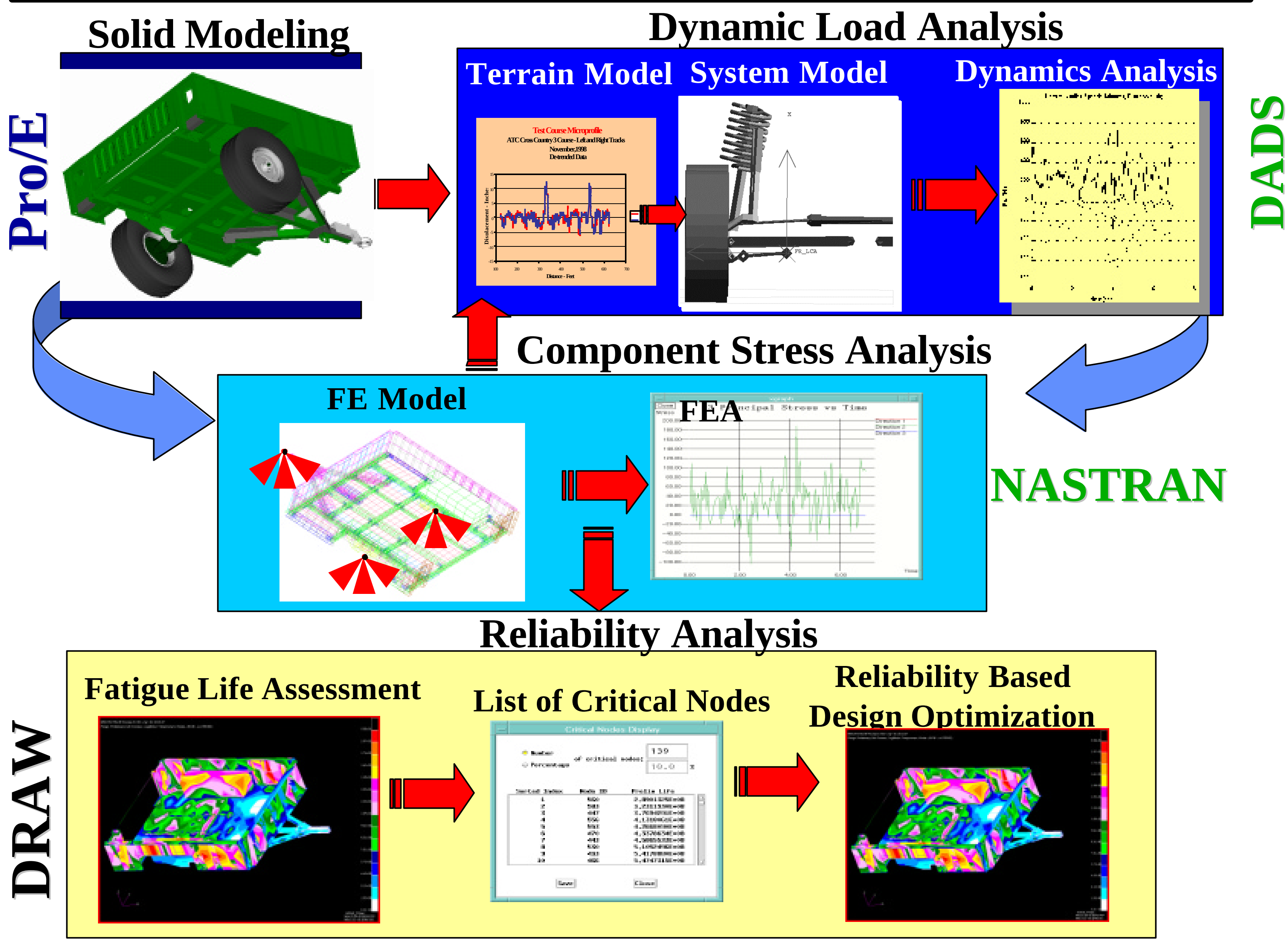
Mechanical PoF: Army Trailer System

Objectives

- ✓ Focus on Fatigue
- ✓ Develop process for dynamic fatigue analysis
- ✓ Replicate drawbar failure
- ✓ Validate dynamics loading from system level to component level
- ✓ Use lab/field test data to validate loading & reliability predictions

Army Mechanical PoF Team: AMSAA, ATC, DTC, TARDEC, AEC, University of Iowa, University of Tennessee

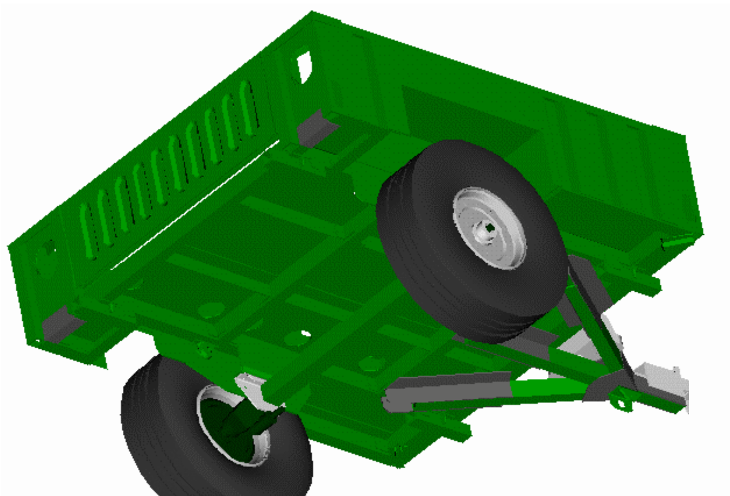
Software Tool Interactions for Dynamic Fatigue Analysis

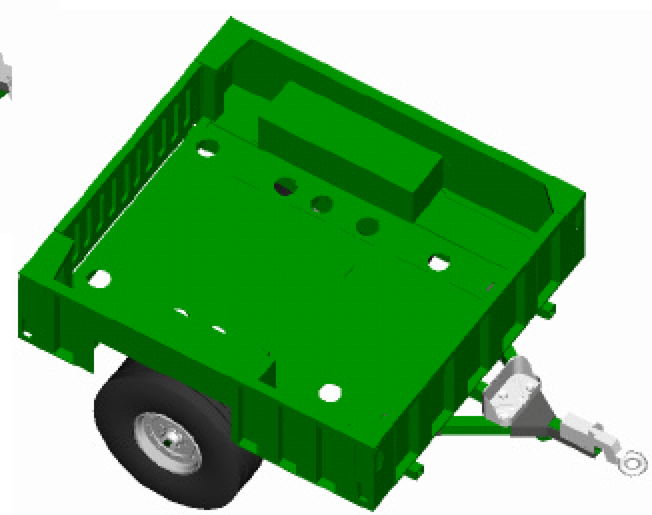


3-D Solid Model in Pro/Engineer

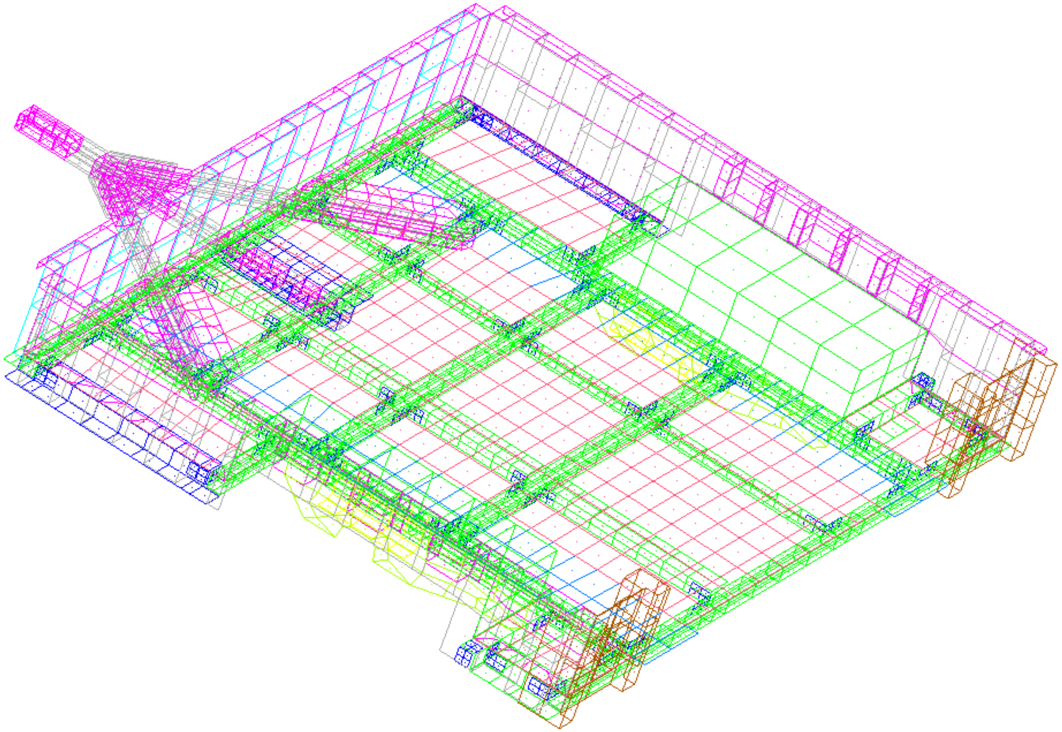
CAD modeling was performed within Pro/Engineer

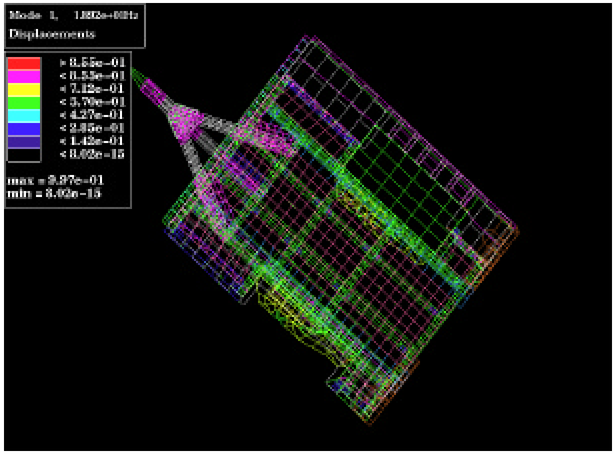
- **Physical measurements and mass/inertia properties used to validate model**
- **Material properties were assigned to each part**
- **Used to develop the bodies defined in dynamic analysis**
- **Used to develop Finite Element Model**



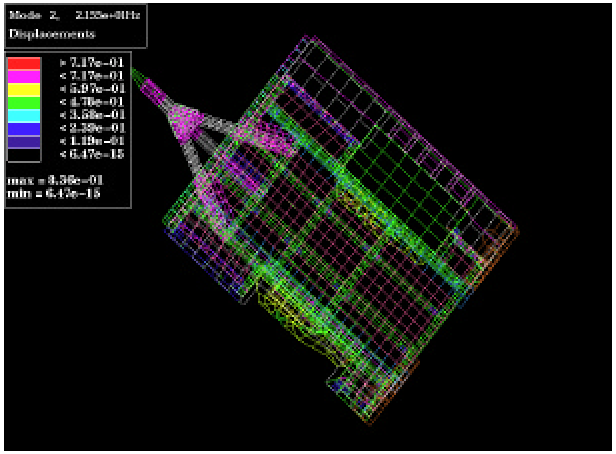


Finite Element Analysis (FEA) Model





Mode 1



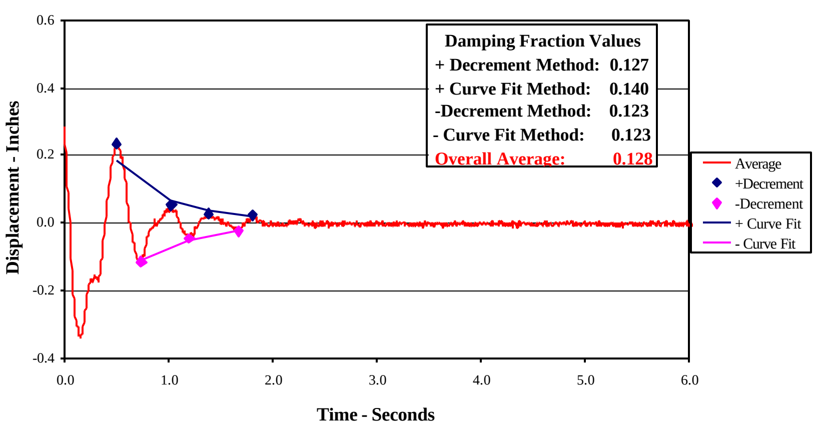
Mode 2

- **FEA performed using NASTRAN**
  - **Calculates vibration modes**
  - **Calculates stress and strain**
  - **Input into fatigue analysis**
- Modal results experimentally validated

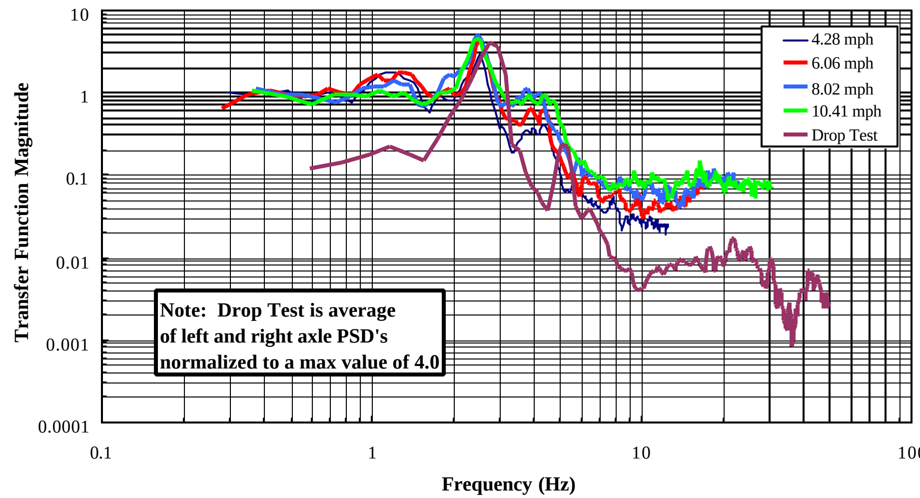
Tire, Axle, & Shock Measurements

- **Tire**
  - ➢Natural frequency and damping (non-rolling)
  - ➢Natural frequency (rolling)
- **Axle**
  - ➢Spring rate obtained from previous modeling effort at RTTC
  - ➢Damping determined from drop test of trailer
- **Shock Absorbers**
  - ➢Performed by Penske Racing Shocks, Reading, PA
  - ➢Force-velocity curve determined using shock dynamometer

Trailer Torsion Bar Dynamic Test
Average Time History From All Vertical Drops
Left Side



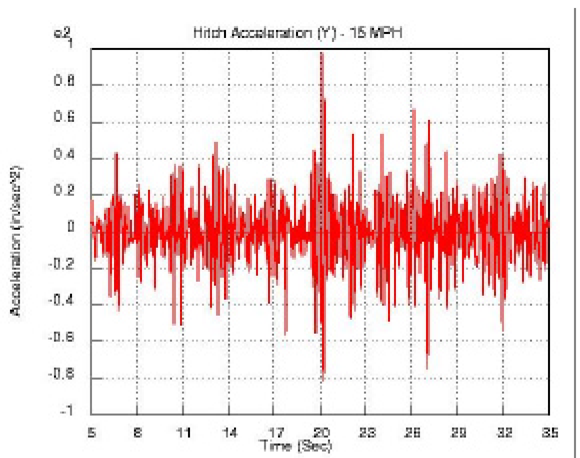
Tire Transfer Function
17 psi Inflation Pressure
ATC Belgian Block Course

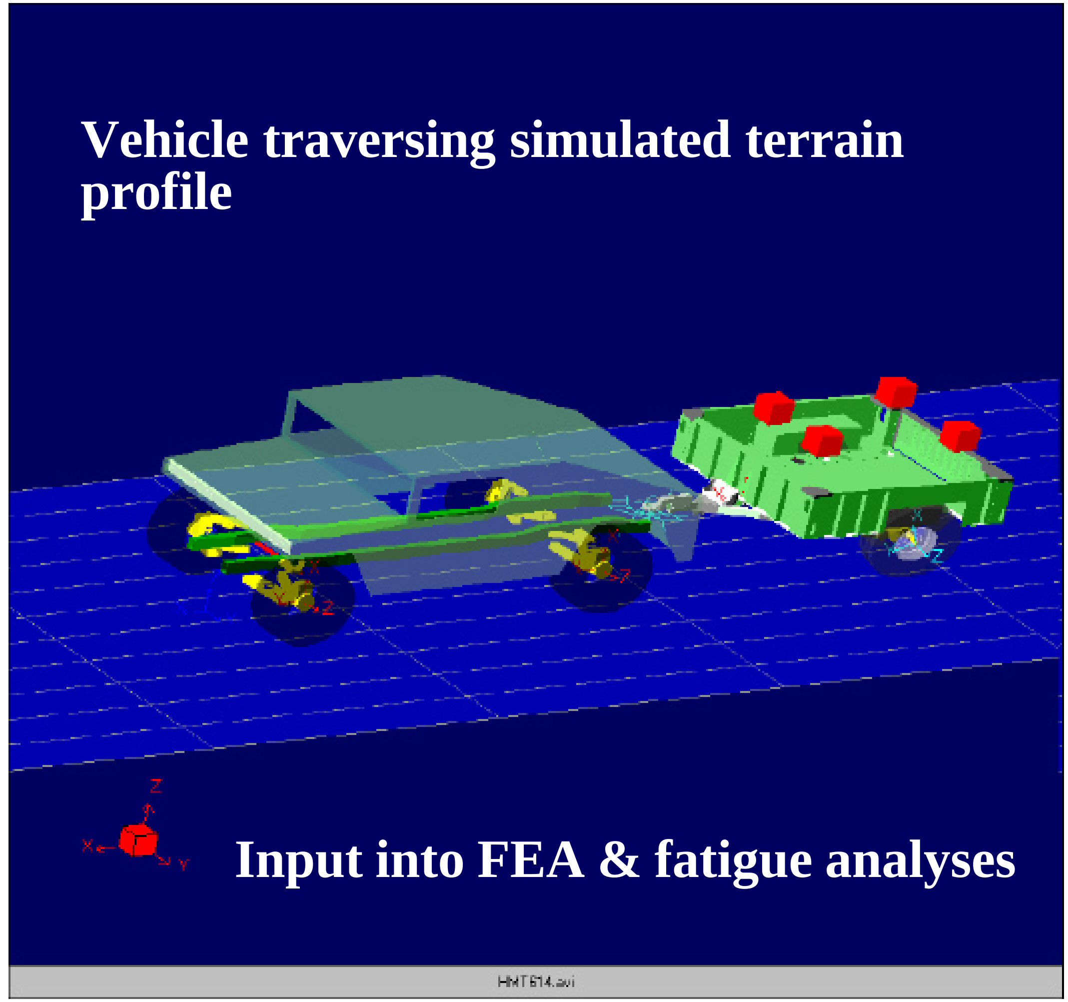


Flexible-Body Dynamic Analysis Model

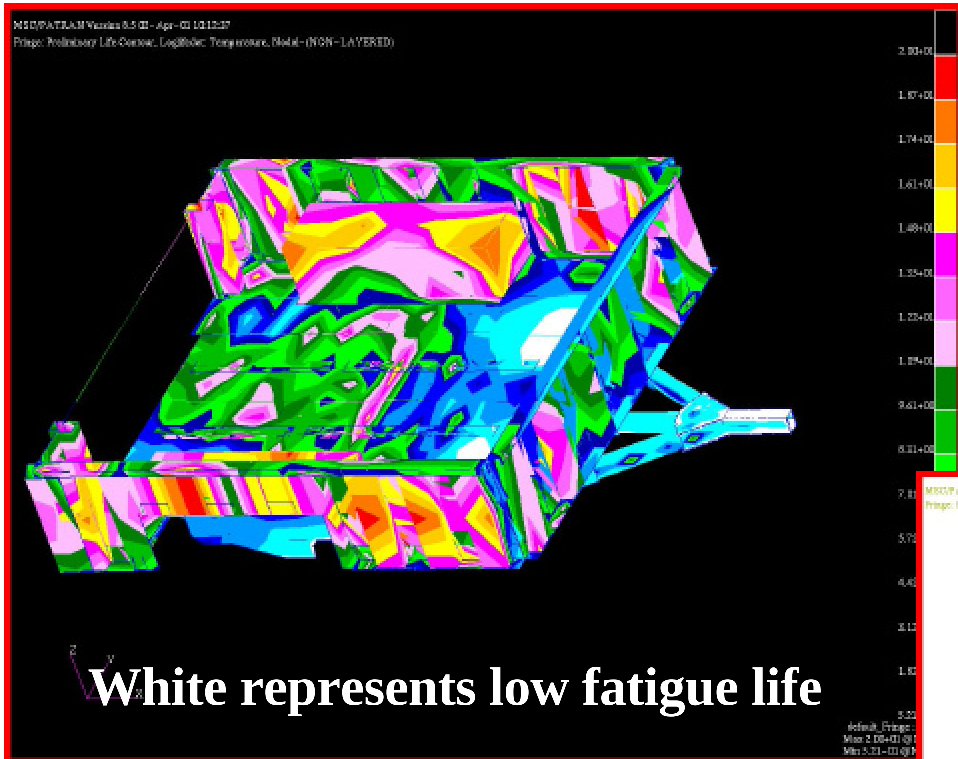
Dynamic Analysis used DADS

- Multi-body approach
- Use input from solid model & FEA model
- Experimental data used for model inputs of tire, shock absorbers & suspension
- Determines force/ acceleration time history at all locations on trailer

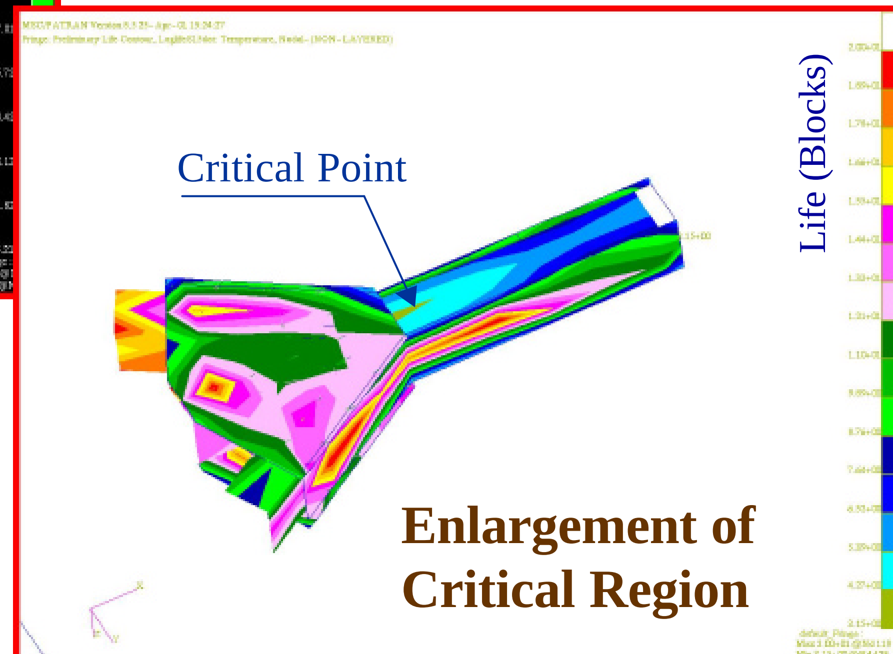




Fatigue Results



Results consistent with failure data on Perryman No. 3 course



Benefits:

- ➢Early identification of failure modes
- ➢Better test planning and design
- ➢Improved maintenance procedures

PoF-Based Prognostics
Life-Consumption Monitoring Demonstration

Determine terrain categories and speeds

- Selected 4 terrain categories from ATC courses: 3-mile straight course, Perryman Cross Country (CC) #1, Perryman CC #2, Perryman CC #3
- Determined average speed for each terrain (50, 35, 25, 15 mph, respectively)
- Terrain and speed equated to vibration severity levels called Smooth Road, Rough Road, Off Road, and Cross-County

Determine vehicles vibration severity in real time

- Terrain Sensor System/Vibration Severity Sensor (TSS/VSS) used to determine vehicle vibration severity levels in real time

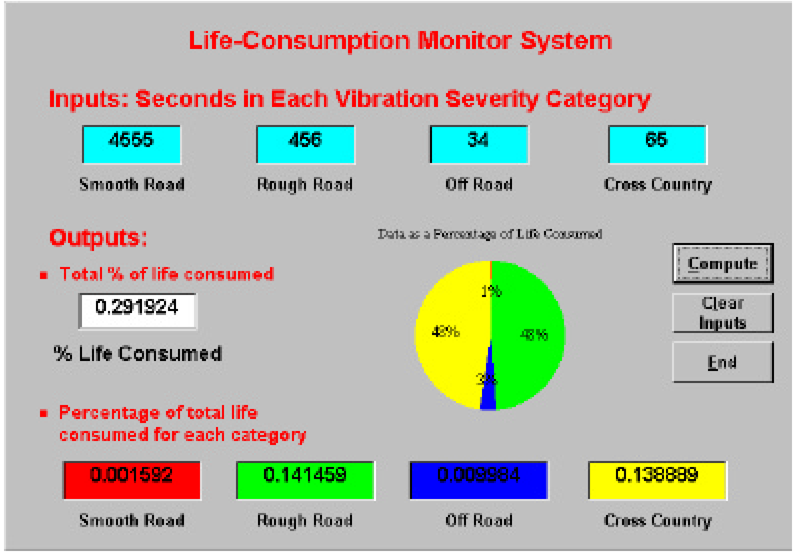
Vehicle LCM Algorithm

- **PoF models simulated trailer life for each terrain/speed (vibration severity)**

Smooth road (SR) life	**= 286128000 seconds**
Rough road (RR) life	**= 322354 seconds**
Off road (OR) life	**= 340560 seconds**
Cross country (CC) life	**= 46800 seconds**

- **Percent damage per vibration severity level per unit time determined**

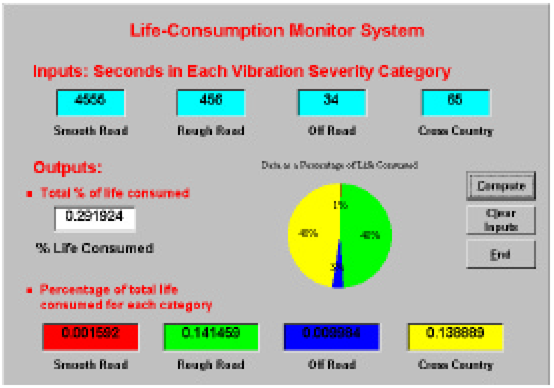
Life Consumed = SR/SR_Life + RR/RR_Life + OR/OR_Life + CC/CC_life



Simple algorithm could be expanded for greater refinement in terrain types and vehicle speeds

Other Prognostics Efforts

- **Working with The Technical Cooperation Program (TTCP) members (UK, Canada, and Australia) to identify and develop techniques for incorporating Physics-of-Failure (stress-history) based prognostics into military platforms.**



- **Conducting FMTV automatic data collection demonstration**
  - **Collect data from system bus & sensors**
  - **Working w/ AMSAA Sample Data Collection**
  - **Working w/ ATC (Volvo truck data collection)**
  - **Examples of data to be collected: Faults codes, vehicle speed, vehicle braking, vibration, shock**
  - **Used for maintenance, prognostics, PoF analyses**

Summary

- Electronics PoF has shown high return on investment and has resulted in significant reliability improvement
  - Design reliability in up-front
  - Determine when can use COTS
  - Commercial best practices
- Mechanical PoF demonstrations very successful
  - The technology enables early assessment of potential fatigue failure problems during the vehicle design and development process
  - Fatigue analysis from nCode used with measured strain data
  - Approach critical for prognostics and life consumption monitoring
- PoF-Based Prognostics is very promising
  - Provides longer lead times than precursor prognostics
  - Demonstration system developed for trailer fatigue
  - International TTCP project is ongoing